another star, suggesting that low-density regions of star formation such as the Taurus Molecular Cloud are the most promising nurseries for planets that eventually develop Earth-like environments. One interesting auxiliary result was the calculation of the odds of Earth being ejected or captured from the solar system by another star prior to the Sun's red giant phase: a scant one part in one hundred thousand!

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Stability of the Upsilon Andromedae Planetary System

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This project studies the dynamical properties of planetary systems that are consistent with the observational data on the three-planet system orbiting the nearby main sequence star Upsilon Andromedae. Some configurations consistent with the data originally announced by the discovery team are found to be stable for at least one billion years, whereas in other configurations planets can be ejected into interstellar space in less than 100,000 years. The typical path to instability involves the outer planet exciting the eccentricity of the orbit of the middle planet to such high values that it ventures close to the inner planet. In some stable systems a secular resonance between the outer two planets prevents close approaches between them by aligning their longitudes of periastron (that is, the orientations of their elliptical orbits). In relatively stable systems, test particles (which can be thought of as representing asteroids or Earth-like planets that are too small to have been detected to date) can survive for long periods of time between the inner and middle planets, as well as exterior to the outer planet. No stable orbits between the middle and outer planets were found.

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Hydrodynamic Simulations of Asteroid Impacts on Venus

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Impact cratering is strongly affected by the presence of an atmosphere. Our solar system offers four relevant targets: Venus, Titan, Earth, and Mars. Our greatest concern is with the Earth, but Venus is the best subject to study, because its atmosphere is about 100 times thicker than the Earth's, and the surface of Venus is randomly peppered with a thousand craters, most of which are apparently little altered since their creation. Thus Venus provides the ideal testbed for theories of atmospheric permeability to stray cosmic bodies—there is both strong atmospheric interaction and enough craters to provide ground truth to calibrate results.

In this study, numerous two-dimensional (2-D) high-resolution hydrodynamical simulations of asteroids striking the atmosphere of Venus were performed. The computations used ZEUS, a grid-based Eulerian hydro-code designed to model the behavior of gases in astrophysical situations. The numerical experiments address a wide range of impact parameters (velocity, size, and incidence angle), but the focus is on 1-, 2-, and 3-kilometer-diameter asteroids, because asteroids of these sizes are responsible for most of the impact craters on Venus. Asteroids in this size range disintegrate, ablate, and decelerate in the atmosphere, yet retain enough impetus to make large craters when they strike the ground. Smaller impactors usually explode in the atmosphere without cratering the surface.

In the simulations, the impactor is broken up by aerodynamic forces generated by the rapid deceleration of the bolide and the shearing flow that develops around it. This results in a complicated and turbulent flow at high Mach number, featuring a broad range of exponentially growing unstable waves. The simulations are sensitive to small differences (both physical and computational) in the initial conditions of the computation. It is found that the shape, resolution, velocity, or other details of the impact can strongly influence which wavelengths grow first, and how quickly. The evolution of each impact is unique, highly chaotic, and sensitively dependent on details of the initial conditions. Atmospheric permeability thus becomes somewhat probabilistic. One lumpy object might fail to reach the surface, while another object identical except for different lumps might leave a 10-kilometer crater. The impact process is chaotic at some level; this study concentrated on extracting robust and useful results from the welter of detail that emerges from the numerical hydro-code simulations. The sensitivity of the computational results to seemingly innocuous and inconsequential differences in the model appears to be a real, physically based characteristic of the impact process, generated by the nonlinear development of the hydrodynamical instabilities. The chaotic character of the impact process adds extra scatter, as it were, to the distribution of results that would already exist because of variations in the parameters of incoming impactors, such as shape, impact velocity, etc.

Because most of the larger impactors disintegrate by shedding fragments generated from hydrodynamic instabilities, a simple heuristic model of the mechanical ablation of fragments was developed, based on the growth rates of Rayleigh-Taylor instabilities. In practice, the range of model behavior can be described with one free parameter. This "ablation" model supplements the more traditional "pancake" model that treats the impactor as a single hydrodynamically deforming body. The two models have different and somewhat overlapping realms of validity. The key distinction between large and small impactors is that compression waves can cross the smaller impactor before the hydrodynamic instabilities mature, thus involving the whole object in the hydrodynamics. By contrast, the larger impactor can have its front face stripped off before the trailing hemisphere is noticeably distorted. For Venus, the pancake model generally works better for impactors smaller than 1–2-kilometer diameter, and the ablation model generally works better for impactors larger than 2–3 kilometers.

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SPACE TECHNOLOGY

Onboard Autonomy and Contingent Planning for Rovers

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The Pathfinder mission demonstrated the potential for robotic Mars exploration, but at the same time indicated the need for increased rover autonomy. The highly ground-intensive control with infrequent communication and high latency limited the effectiveness of the Sojourner rover. This project set out to increase the flexibility and robustness of Mars rovers by developing a contingent sequence language, a contingent planner/scheduler to support generation of such sequences, and an onboard executive system that can execute contingent sequences, manage resources, and perform fault diagnosis.

The first step was the design of a new commanding language, called the Contingent Rover Language (CRL). A key feature of CRL is that it enables the encoding of contingent plans specifying what to do if a failure occurs, as well as what to do if a serendipitous science opportunity arises. For example, a CRL plan could specify the following contingent rover behavior: when a failure occurs, execute a contingency plan to recover from the failure; if none is available, then execute a contingency plan to acquire additional data to support failure diagnosis and recovery by the ground operations team.

The current autonomy architecture (see figure 1) consists of a contingency planner/scheduler, a conditional executive, a resource manager, and a

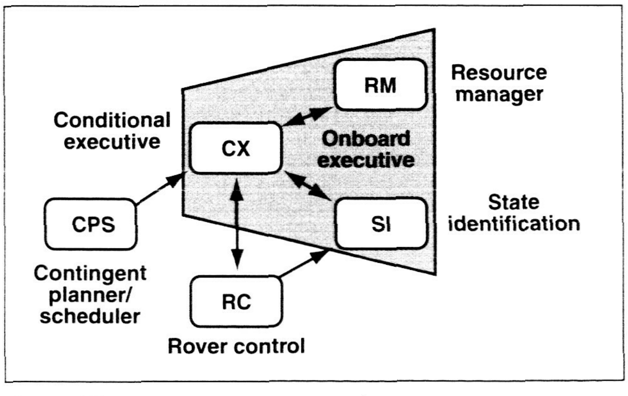

Fig. 1. The rover autonomy architecture.